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Breaching of Triple-Brick Walls: Numerical Simulations

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Abstract

Explosive wall breaching will be a key war-fighter capability in future military operations by dismounted soldiers in urban terrain environments where the close proximity of urban structures, possibly occupied by noncombatants, significantly restricts the use of large demolition charges or large caliber direct-fire weapons. Because of this requirement, the US Army has focused considerable attention and resources to optimize breaching activities in urban terrain. As part of the Army's effort, the US Army Engineer Research and Development Center (ERDC) is conducting experimental and numerical investigations to improve wall breaching methods. The ongoing experimental and numerical programs will conduct comprehensive breaching research on a full range of urban construction materials. As a first step in this process, the ERDC conducted a successful baseline study of Composition C4 (C-4) breaching effectiveness against steel-reinforced-concrete walls. Recently, the research effort was extended to triple-brick walls. Numerical simulations of two selected experiments were conducted using the coupled Eulerian- Lagrangian code Zapotec. In these simulations, the brick and mortar were modeled as Lagrangian materials, and the C-4 was modeled as an Eulerian material.

1. Introduction

The US Army has focused considerable attention and resources to optimize military operations in urban terrain (MOUT). It is essential that warfighters and battle planners have accurate information regarding the effects of Army weapons against the various types of wall targets (such as reinforced concrete, brick and block masonry, and adobe) commonly found in MOUT areas of interest. Required weapon-target information includes knowledge of the degree of damage to the target produced by a given weapon, along with accurate predictions of the expected airblast field on both sides of the target wall. Predictions of hazards from primary fragments (from the weapon casing) and secondary debris (from break-up of wall materials) are also of critical importance. Lack of information defining weapon-structural target interaction can result in inaccurate and lengthy targeting, excessive collateral damage, and possible endangerment of noncombatants and friendly forces.

In an on-going multiyear experimental and numerical program, the ERDC has conducted comprehensive demolition breaching research on a full range of construction and material types, and will fully validate new multifunctional breaching procedures across the spectrum of desired missions. As a first step in this process, ERDC conducted a baseline study of C-4 breaching effectiveness against steel-reinforced concrete walls.

An earlier paper[1] addressed two experiments and the simulations of those experiments, where a group of 11 blocks of C-4 and a single block of C-4 were detonated against target walls. This paper documents the expansion of that earlier work to include breaching effectiveness against triple-brick walls. Two C-4 contact charge configurations were investigated: a 2.27 kg (5 lb) right-circular cylinder and a 2.27 kg sphere. Experimental data were obtained for both charge configurations.

2. Numerical Codes

The coupled Eulerian-Lagrangian computer code Zapotec[2], developed by Sandia National Laboratories, was used to perform the wall breaching simulations. The Zapotec code links the CTH and Pronto3D codes; both CTH and Pronto3D run concurrently and all run on massively parallel machines. CTH[3], an Eulerian shock physics code, performs the Eulerian portion of the analysis, while Pronto3D[4] performs the Lagrangian analysis. As stated in Reference 2, Zapotec was developed to solve a class of problems not readily handled by either Eulerian or Lagrangian methods alone, in which the materials involved exhibit vastly differing degrees of deformation. Example applications include earth penetration, blast loading on structures, and anti-armor applications.

The primary materials of interest in these simulations were the brick and mortar in the walls, which were modeled in the Lagrangian code Pronto3D. Pronto3D is a large-strain explicit dynamics code that employs the finite element method to solve the equations governing the behavior of solids subjected to large magnitude short-duration load histories. Pronto3D applies the finite element method to accomplish the spatial integration of the governing partial differential equations; the temporal integration is performed with an explicit central difference scheme. To satisfy material frame indifference (the principle that stresses are created by actual straining and not by rigid body motions), Pronto3D uses a Green-Naghdi treatment of rotation. This co-rotational reference frame permits implementation of constitutive models into Pronto3D without regard to finite rotations.

3. Constitutive and Equation of State Models

The brick and mortar in the simulations were modeled in Pronto3D using the Karagosian and Case (K&C) concrete model. The K&C concrete model is an extensively modified version of Model 16 in DYNA3D[5]. A detailed description of the model is given in Malvar, et al.[6]. The volumetric response is calculated using a tabulated equation of state, where pressure and unloading bulk modulus are prescribed as a function of volumetric strain[6]. The volumetric and deviatoric responses in the model are decoupled. Three fixed surfaces, a yield surface, an ultimate surface, and a residual surface, define the material's shear behavior in deviatoric stress-pressure space. A material is fully elastic when the stress state is below or within the yield surface. When a material's stress path penetrates the yield surface, plastic deviatoric strains begin to accumulate. The ultimate surface limits the maximum deviatoric stress within the material. After contacting the ultimate surface, e.g., during triaxial compression boundary conditions, the material will soften and lose strength until it reaches the residual surface, which defines the strength of the material in its fully damaged state. Damage is based on an evolution law, which is a function of an accumulated effective plastic strain metric identified as $d\lambda$.

The C-4 explosive charges were modeled in CTH with the Jones-Wilkins-Lee equation of state, which is available in most hydrocodes. As stated in Reference 7, it is "popular because it is simple and because the parameters are (usually) determined from experimental data."

4. Scalability

The simulations presented in this paper were performed on the Cray XT3 system at the ERDC Major

Shared Research Center (MSRC). The XT3 has 4,160 processing nodes; each node contains a 2.6-GHz Opteron 64-bit dual-core processor and dedicated memory. A series of simulations were performed to assess the scalability of Zapotec on the XT3. The analysis was a small-scale problem representing colliding blocks of concrete; the Microplane model[1,8] was used to simulate the concrete. The size of the problem was maintained constant and the number of processors varied. The simulation would not run on fewer than eight processors due to the memory requirements of the problem. The input/output (I/O) for these simulations was kept to a minimum to better measure the compute performance of the code. The measured versus ideal performance for Zapotec on the XT3 is plotted in Figure 1. For comparison purposes, the results from the same simulations conducted on a Compaq SC45 are also plotted. For 128 PE's, the measured run time on the SC45 was 2.48 times longer than the run time on the XT3.

5. Field Experiments

During the field experiments, triple-brick walls with nominal dimensions of 2.7 m×2.7 m×0.3 m were subjected to the explosive loading environments produced by contact detonation charges. The walls were constructed from solid severe-weathering bricks having standard US dimensions of 57×95×203 mm (2.25×3.75×8 in) and a mean unconfined compressive strength of 73 MPa. The mortar was prepared from a Type-S mortar mix, which produced an unconfined compressive strength of 12 MPa. The walls were constructed according to the guidelines set forth in Reference 9, which specifies a common bound pattern with full-length headers every fifth or sixth course (Figure 2). The walls were built into metal frames, which allowed several walls to be built at one time and allowed the walls to be easily moved (Figure 3). The target walls were attached in a vertical orientation to a reusable reaction structure (Figures 4 and 5). The reaction structure has external dimensions of 3.68 m (12 ft) high by 3.68 m (12 ft) wide by 1.83 m (6 ft) long. The target walls were connected to the structure using a series of high strength bolts to ensure the wall was securely attached and flush with the reaction structure (Figure 5). Attachment of the target walls to the reaction structure created an enclosed room with interior dimensions of approximately 2.74 m (9 ft) high by 2.74 m wide by 1.83 m deep.

Two experiments were performed on identical triple-brick walls. The explosive contact charges were made of C-4 and each charge had an explosive mass of 2.27 kg (5 lb). Two charge geometries were used, a sphere (7.0 cm in radius) and a cylinder (3.4 cm in radius and

39.4 cm in length); the center of gravity of each charge was placed opposite the center of each wall face. The flat end of the cylindrical charge was placed in contact with the wall.

The spherical charge produced a irregular shaped breach hole in the 0.3 m thick wall (Figure 6); the dimensions of the breach hole were approximately 25 cm (10 in) high and 25 cm wide. The cylindrical charge did not breach the wall (Figure 7). There was spall off of the back side of the wall and front face cratering. The crater was irregularly shaped (approximately 25 cm high and 25 cm wide) with a maximum depth of less than 9 cm. Posttest inspection of the walls indicated damage to the walls was local to the position of the charges; outside of that region, the walls appeared to be in pristine condition.

6. Numerical Simulations

The primary goal of this numerical effort was to evaluate the ability of Zapotec to simulate the wall response observed in the experiments. Numerical simulations of both completed experiments were conducted. In these simulations, the brick and mortar were modeled as Lagrangian materials, and the C-4 was modeled as an Eulerian material. The brick and mortar were simulated with the K&C concrete model. To keep the computational mesh as small as possible and due to the general symmetric nature of the experiments, a quarter symmetry model of the wall was constructed (Figure 2). The Lagrangian mesh for the wall required 2.4 million elements and nodes; the Eulerian meshes were approximately 12.3 million cells. A typical run used 256 processors and required 15 hours to obtain 30 milliseconds (ms) of simulation time. To reduce the required CPU time, CTH was turned off after 0.5 milliseconds of simulation time and only Pronto3D continued to run. At 0.5 milliseconds, the blast pressures were close to ambient and the wall response is driven by the inertia induced by the blast.

In the Lagrangian code, failure was simulated by a process of "adaptive element deletion"[4] or element death. This process of element death was used to numerically erode material in the triple-brick walls and to remove highly distorted elements. Any element variable or material model state variable may be used to control element death in Pronto3D. We chose the $d\lambda$ state variable within the K&C model to control element death in these simulations; this state variable represents a measure of inelastic strain within the material. A limiting $d\lambda$ value of 0.0001 was selected to produce element death. This value was selected based on trial simulations with $d\lambda$ parameters for element death values ranging between 0.0001 and 0.03.

Comparisons of the breach holes and craters produced in the experiments and in the simulations for the two contact charges are presented in Figures 6 and 7. The quarter-symmetry geometry from each simulation has been reflected once to aid the visualization. The breach hole generated in the spherical charge simulation is slightly undersized when compared to the experiment; however, the differences between the breach-hole dimensions are less than ten percent. The simulation exhibited more damage to the wall away from the charge location than was observed in the experiment. The cylindrical charge simulation, like the experiment, did not produce a breach hole in the wall. As in the spherical charge simulation, this simulation also predicted more damage to the wall at locations away from the charge than was observed in the experiment.

7. Summary

The K&C concrete constitutive model accurately simulated the brick and mortar behavior for two different charge configurations. Based on the breach hole and crater dimensions, the calculated results were within approximately ten percent of the experimental values. Future efforts will address the propagation of the blast through the breach hole in the triple-brick wall and into the room. We will also attempt to calculate the velocity of the fragments ejected from the wall by using Zapotec's donation feature. In this process, deleted Lagrangian material is donated to the Eulerian mesh.

System Used

The Cray XT3 system at the ERDC MSRC.

Computational Technology Areas

Computational Structural Mechanics

Acknowledgments

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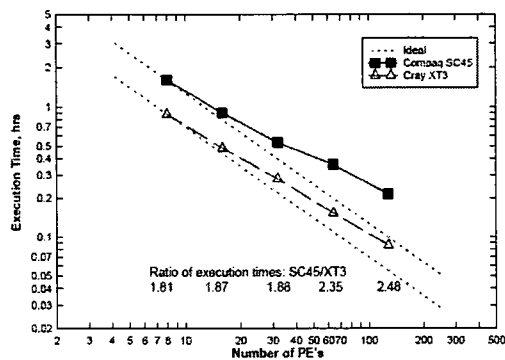
Figure 2. Front and cross-sectional view of triple-brick wall
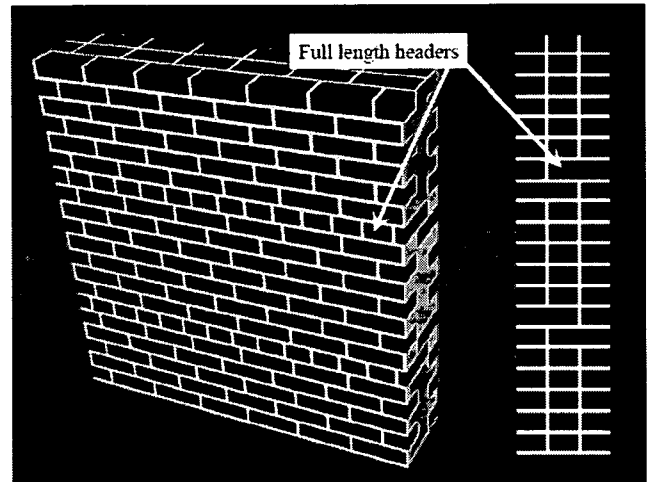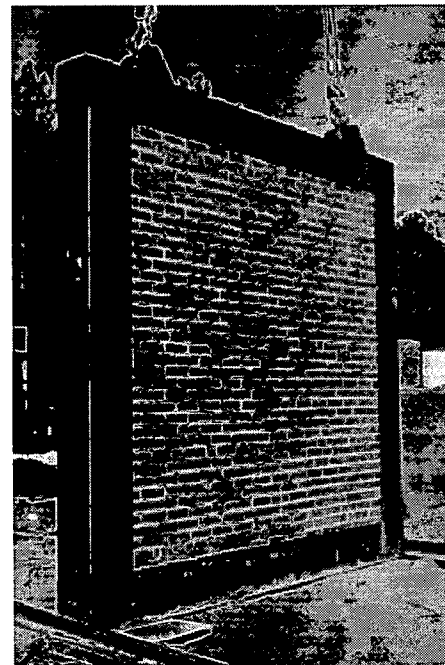

Figure 3. Frame containing triple-brick wall

Ratio of execution times: SC45/XT3
1.81   1.87   1.88   2.35   2.48

Figure 1. Scalability study for Zapotec
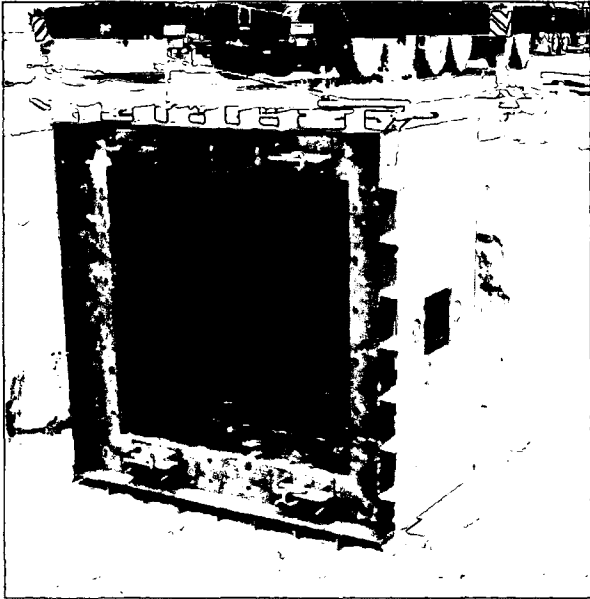
10

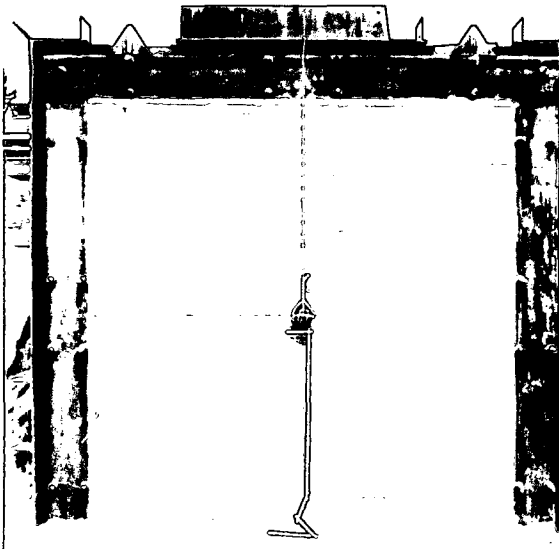**Figure 4. Reaction structure in-place at test site**

Figure 5. Reaction structure with triple-brick wall in place
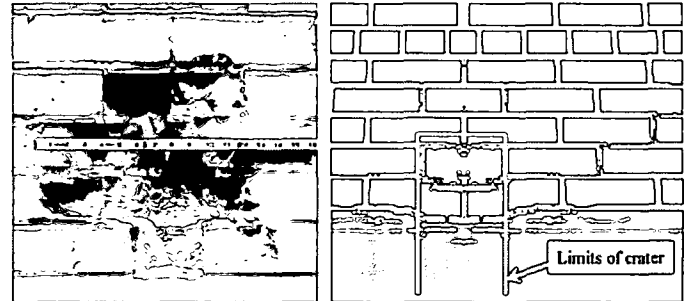

Figure 6. Experiment versus simulation: spherical charge

Figure 7. Experiment versus simulation: cylindrical charge